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Mechanical Property Comparison of the Soviet BS-41 and the US M993 Armor-Penetrating Cores

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Mechanical Property Comparison of the Soviet BS-41 and the US M993 Armor-Penetrating Cores

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14. ABSTRACT A comparison of the Soviet Union's BS-41 and US M993 armor-penetrating cores is made. The BS-41 core is composed of coarse-grained tungsten carbide (WC) cemented in nickel, while the M993 core is a fine-grained WC cemented in cobalt. The M993 core was determined to have superior hardness and indentation toughness. The superior properties of the M993 core are attributed to its finer grain size and more uniformly dispersed binder phase.					
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1. Introduction

Tungsten carbide (WC) has high hardness and good wear resistance, but low toughness. The toughness can be greatly increased by cementing it in a ductile second phase, such as cobalt or nickel; however, a certain degree of hardness must be sacrificed. This combination of properties leads to a variety of applications, ranging from jewelry to armor-piercing projectiles. Despite having origins in the First World War, this material system continues to undergo advancement with expanding commercial applications.^{1,2} Fine-grained WC was introduced during the 1940s in the form of superior mining tools, but recently more detailed scientific studies have focused on producing WC materials with the highest strength and toughness values possible. The adjectives used to describe this material must be clarified based on the time period of their development. In the 1940s “fine-grained” described starting powders between 0.5 and 3.0 μm , while beginning in the 1990s, fine-grained has been used to describe nanocrystalline starting powders (20–50 nm).³ The differences in WC from the past to the present can be better observed by comparing the Soviet-manufactured BS-41, from the WWII era, and US current field-issue M993 armor-penetrating cores. Both of these armor-piercing projectiles use a cemented WC as the core material.

The BS-41 was introduced by the Soviet Union during World War II as an antitank round. It was able to penetrate German light and medium tanks, such as the Panzer II and Panzer IV, at distances up to 150 m using incendiary tips. The BS-41 is a WC material containing approximately 10 wt% nickel as the binder material and has a density of 14.53 g/cm³.⁴ Additional information on the BS-41 can be found in Quittman⁵ and Grady⁶. The M993 is a small-caliber, armor-piercing round currently fielded by the US Army. Its core is tungsten carbide with 11.6 wt% cobalt, resulting in a density of 14.37 g/cm³.

2. Procedure

The chemical composition and phase analysis of both materials were determined using X-ray diffraction (XRD) analysis. XRD was conducted on bulk specimens using a Rigaku MiniFlex II unit with a Cu K-alpha radiation source. Scans were conducted between 25° and 85° 2 θ at increments of 0.25°/min. Polished, bulk specimens were also examined using scanning electron microscopy (SEM) to identify elemental composition using energy dispersive spectroscopy (EDS) and to investigate the microstructure.

The mechanical properties of the cores were compared using indentation testing methods. All indents were made on material that was ground flat and then polished using 15-, 9-, 3-, 1-, and finally 1/4- μm diamond suspension, in sequence. A Wilson Tukon 2100B hardness tester was used to create indents on polished sections of each material, and all crack lengths were measured on a Leica optical microscope with accompanying software. ASTM C1326-13⁷ was used to determine the Knoop hardness of both materials. A 5×5 grid of Knoop indents was placed on each sample using a 2-kgf (19.8-N) load. The design of the Knoop indenter reduces the likelihood of cracking when indenting more brittle materials, which allows indent impressions to be more easily measured. The hardness of each material was calculated by measuring the long Knoop diagonal for each indent in the grid and applying Eq. 1, where P is the load (kgf) and d is the long diagonal length (mm).

$$HK = 0.014229 * \left(\frac{P}{d^2} \right) [\text{MPa}]. \quad (1)$$

The Palmqvist fracture toughness (W_K) was determined following the procedures in ISO 28079⁸ using a row of 5 Vickers indents made under a 50-kgf (491-N) load. Corner cracks are vital in measuring indentation-fracture toughness values. These corner cracks were measured and used to calculate the Palmqvist fracture toughness by applying Eq. 2.

$$W_K = A * \sqrt{HV} * \sqrt{\frac{P}{\sum l}} [\text{MPa m}^{1/2}], \quad (2)$$

where A is a fitting constant ($A = 0.0028$), HV is the hardness (N/mm^2), P is the indentation load (N), and $\sum l$ is the sum of the crack lengths (mm).

3. Results and Discussion

3.1 Composition

The BS-41 and M993 cores were confirmed to be cemented tungsten carbide via XRD. Figure 1 shows the BS-41 and the M993 spectra, respectively, both having characteristic peaks that match tungsten carbide. The BS-41 core is cemented in nickel, while the M993 core is cemented in cobalt. Both binder materials have very similar XRD characteristic peak locations, therefore EDS was used to confirm these results.

XRD BS-41 and M993 Cores

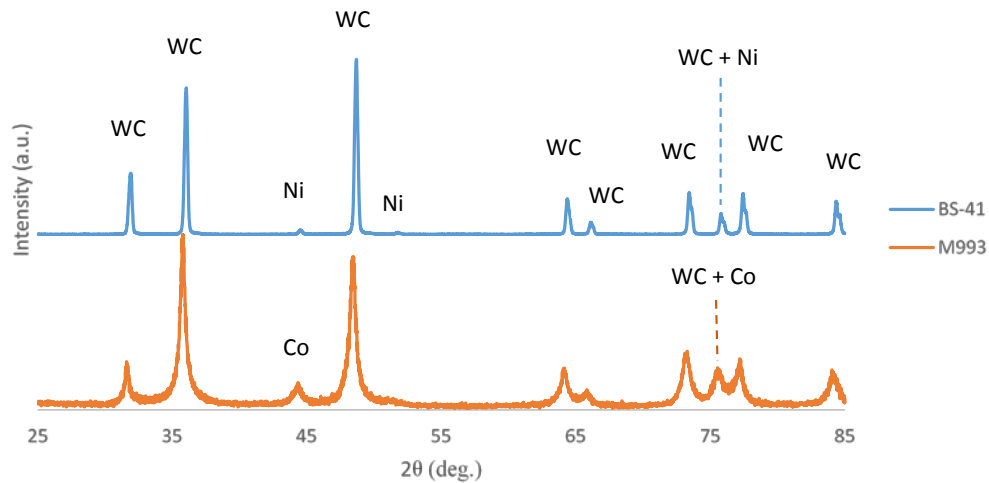


Fig. 1 XRD patterns for BS-41 and M993 cores

Figure 2 shows EDS chemical analysis for the respective core materials. Nickel and cobalt are comparable binders, as tungsten carbide has a similar solubility in both metals.⁹ In general, nickel and cobalt are similar in properties due to their close proximity on the periodic table; however, there are key differences. At room temperature cobalt is stable in the hexagonal closed pack (HCP) structure, nickel in a face-centered cubic (FCC) structure, and WC in an HCP structure. Materials with similar lattice structures will have less misfit at their interface and thus less interfacial strain energy that can increase the likelihood of crack initiation and propagation at the interface.

EDS BS-41 and M993 Cores

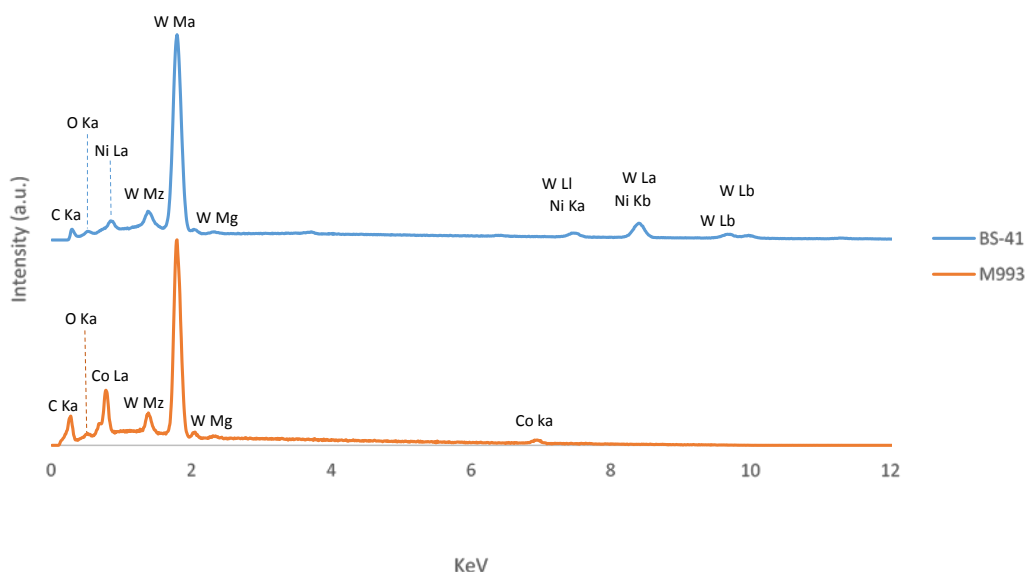


Fig. 2 EDS spectra for BS-41 and M993 cores

3.2 Microstructure

SEM images with EDS spot labels are shown in Fig. 3. The grain size of the M993 core is small relative to the BS-41 and appears to be better encapsulated by the binder phase. These microstructural features could explain differences in the properties of these 2 cores. The finer grains increase the hardness of the M993 core,¹⁰ while the uniform distribution of the binder phase allows for higher indentation-fracture toughness. ASTM Standard E112-13¹¹ was used to calculate average grain size by drawing a line, of fixed length, on both SEM micrographs, counting the number of grains intersected, and dividing the actual length of the line by the number of grains counted. (This was performed using 3 lines on each image to calculate an average grain size). The BS-41 core had an average grain size of 5.2 μm , while the M993 core had an average grain size of 1.5 μm . These smaller grains may contribute to the greater hardness of the M993 core as well as its superior indentation-fracture toughness.

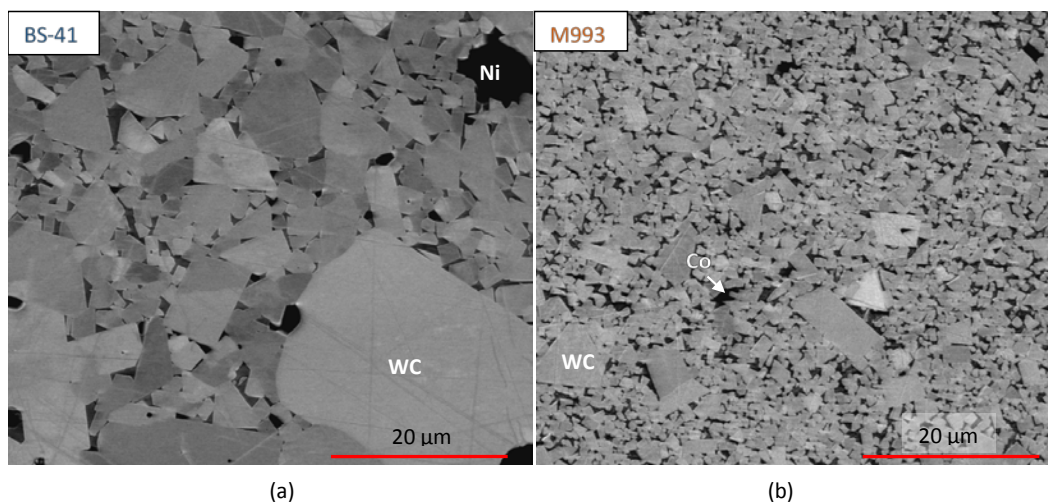


Fig. 3 SEM images of the a) BS-41 and b) M993 microstructures

Optical micrographs of Knoop and Vickers indentations can be seen in Figs. 4 and 5, respectively. The darker regions observed in these figures are most likely the result of the binder phase being removed preferentially during polishing, while the very light regions are still-present binder and the intermediate shade is tungsten carbide. The BS-41 indentation is surrounded by cracking, while the M993 indentation appears to be crack free. The BS-41 impression also shows very large, dark regions, leading one to believe that the binder phase is not well dispersed throughout the tungsten carbide. This is in agreement with what was observed in the SEM images.

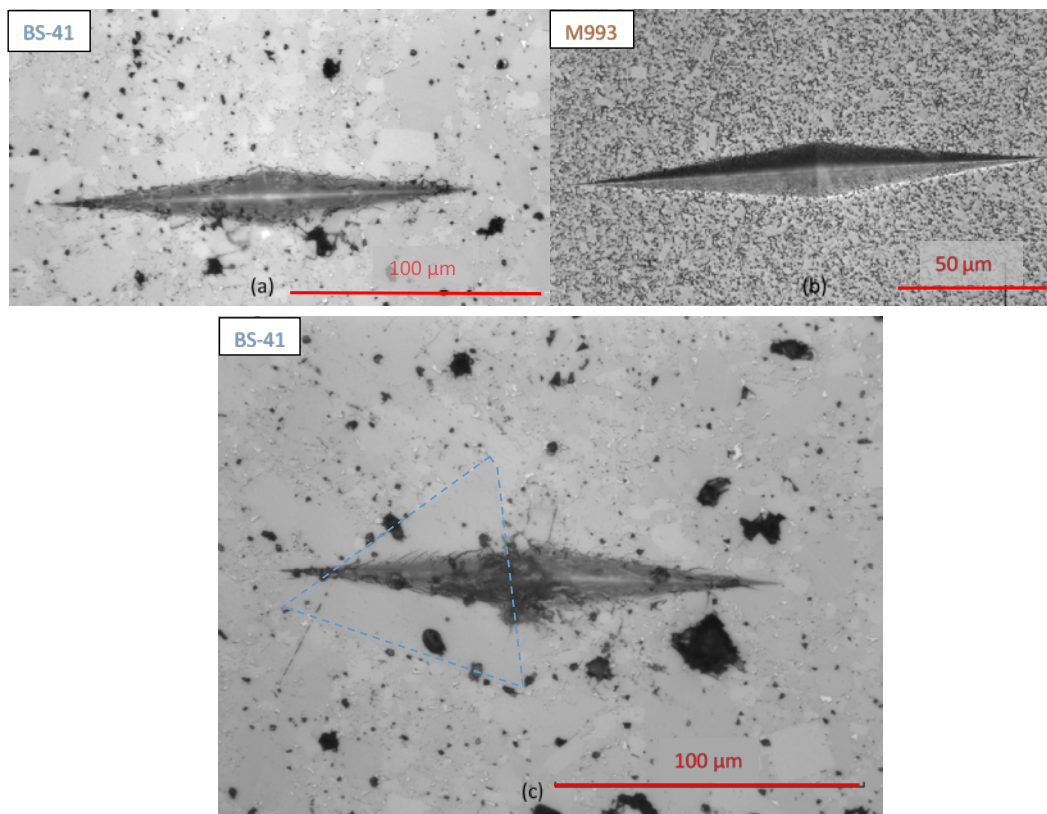


Fig. 4 Optical images of Knoop indentation in a) BS-41, b) M993, and c) BS-41 (different region)

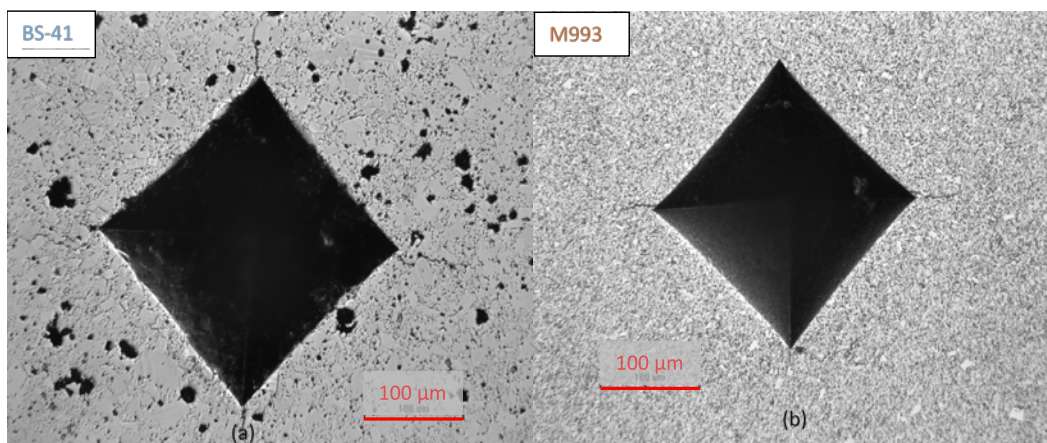


Fig. 5 Optical images of 50-kg Vickers indentations in a) BS-41 and b) M993

3.3 Properties

The Knoop hardness, Palmqvist fracture toughness, and indentation/crack statistics were used to compare the core materials. The hardness and Palmqvist fracture toughness are summarized in Table 1. The data show that the M993 material is approximately 10% harder and 25% tougher than the BS-41 material, which agrees with composition and microstructural analysis.

Table 1 Percentage unsuitable indents and crack types A, B, and C in BS-41 and M993 cores

Indent/crack characterization	BS-41 (%)	M993 (%)
Unacceptable indents	20	0
Crack at tip	35	0
Crack at side	100	0
Spall	100	0

The acceptability of the indents for calculating Knoop hardness was determined using the guidelines identified in the Figure 4 schematic of ASTM C1326-03.⁷ The BS-41 core rendered 20% unacceptable indents, while the M993 core produced none. Of the remaining 20 BS-41 indents used to average the data, 35% displayed cracks from the long diagonal tips of the indents (type A) and 100% displayed cracks emanating from the sides of the indents (type B) as well as spallation (type C). Minimal to no cracking was observed in the M993 indents. Table 2 includes direct comparisons of these crack statistics.

Table 2 Average Knoop Hardness and Palmqvist fracture toughness values for each core

Core	HK ₂ (GPa)	Palmqvist fracture toughness (Wk) (MPa m ^{1/2})
BS-41	11.0 ± 0.7	~ 14
M993	12.5 ± 0.2	~ 20

The Palmqvist fracture toughness values in Table 1 are an approximation and are probably an overestimation of the actual fracture toughness. The Palmqvist method relies on the formation of cracks at the tips of the Vickers indentations to calculate the toughness. An examination of the Vickers indentations showed that cracks did not form at all 4 indentation tips on every indent and the crack lengths varied drastically from one tip to another on the same indent and from indent to indent. This was the case for both materials. Previous research¹² has shown the Palmqvist method has serious limitations and it is not recommended for determining the fracture toughness of cemented carbides. The ductile binder phase, along with the

residual compressive stresses commonly present on the surface of this class of materials, influences the formation of cracks at the tips of hardness indentations.

The observations from the optical and SEM micrographs allow one to better analyze why the BS-41 core's indentations displayed cracks while the M993 core did not. As the indent is pressed into the BS-41 core, certain regions are harder than others are due to the differences in grain sizes and binder content. These variations in hardness and fracture toughness allow individual areas of the material to respond to indentation differently. This mismatch contributes to the indent observed in Fig. 4a. Local, harder regions will resist penetration of the indenter to a greater extent than softer regions, causing additional cracks at their interfaces. For example, Figs. 4a and 4c both are BS-41, but Fig. 4c is of an indent impression on top of a large grain (outlined). At the grain boundary, the indentation shows a spall caused by the mismatch in local hardness and fracture toughness, which is due to the large grain size and binder distributions. The M993 core, with a finer grain size and more uniform binder distribution, displays none of the effects of local mismatch. When deformed, the material responds the same from region to region.

4. Conclusion

The results of this analysis show that the M993 core displays higher hardness and indentation-fracture toughness than the BS-41 core. Each material was confirmed to be cemented tungsten carbide by XRD structural analysis, and the binder material was identified via EDS chemical analysis. Both materials have comparable binder concentrations, but cobalt has a crystal structure that matches WC (HCP). The differences in both these material systems are presumed to be the starting materials, the processing that led to the microstructures of both materials, and the composition of the binder material. When compared with the BS-41 core, the higher mechanical properties of the M993 core are attributed to the finer and more-uniform grains as well as the uniform distribution of the binder phase in the core. With a cobalt binder, smaller grains, narrow grain-size distribution, and a finer microstructure, the M993 core outperforms the BS-41 core in hardness and indentation-fracture toughness but is slightly less dense.

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List of Symbols, Abbreviations, and Acronyms

ARL	US Army Research Laboratory
EDS	energy dispersive spectroscopy
FCC	face-centered cubic
HCP	hexagonal closed pack
SEM	scanning electron microscopy
WC	tungsten carbide
XRD	X-ray diffraction

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